Simulations of beams in plasmas for Heavy Ion Fusion

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19th International Symposium on Heavy Ion Inertial Fusion
Berkeley, CA, USA – August 12-17, 2012

Work performed for U.S. D.O.E. by U.C. LBNL under contract DE-AC03-76F00098 and LLNL under contract DE-AC52-07NA27344.

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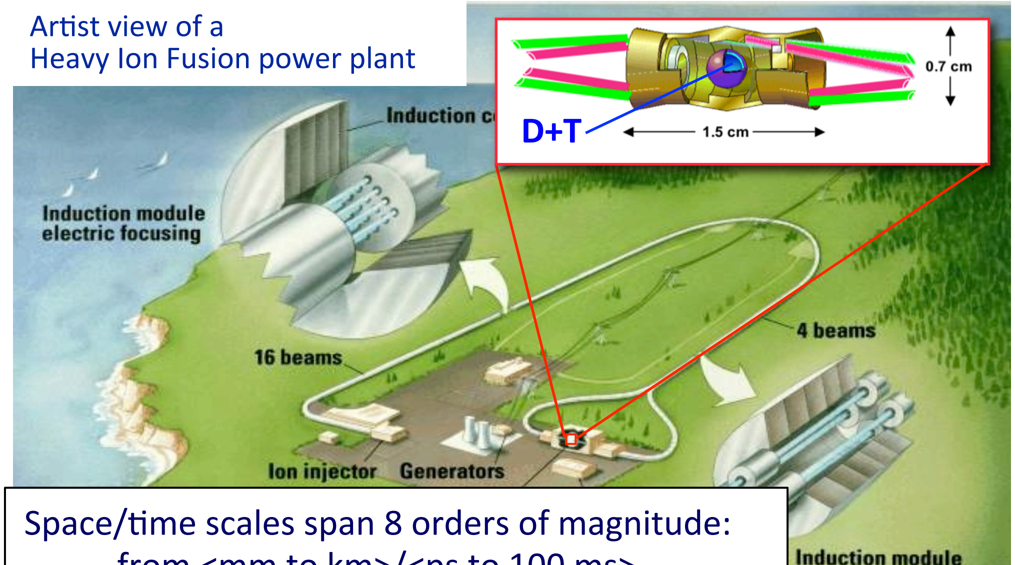
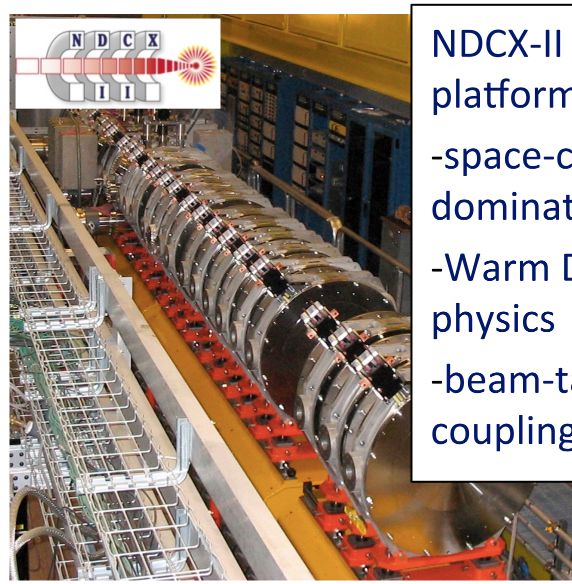
The Heavy Ion Inertial Fusion (HIF) program is studying the science of ion-heated matter, as well as drivers & targets for inertial fusion energy

Artist view of a
Heavy Ion Fusion power plant



Space/time scales span 8 orders of magnitude:
from <mm to km>/<ps to 100 ms>



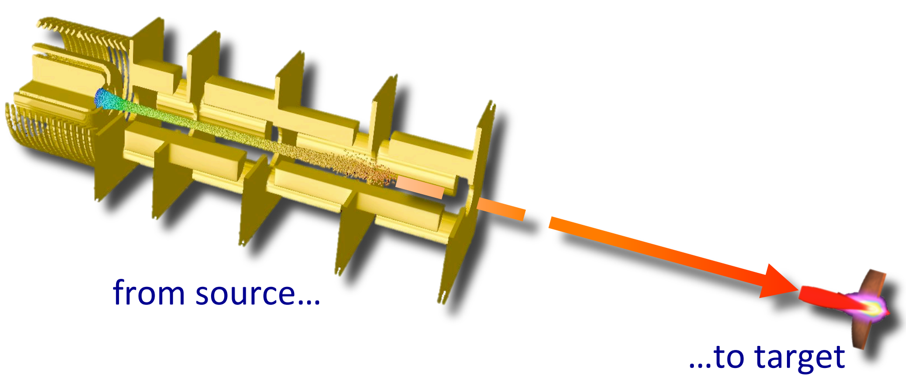
NDCX-II is HIF's new platform for studies of

-space-charge-dominated beams

-Warm Dense Matter physics

-beam-target energy coupling

Simulation goal – integrated self-consistent predictive capability



including:

- beam(s) generation, acceleration, focusing and compression along accelerator,
- loss of particles at walls, interaction with desorbed gas and electrons,
- neutralization from plasma in chamber,
- target physics and diagnostics.

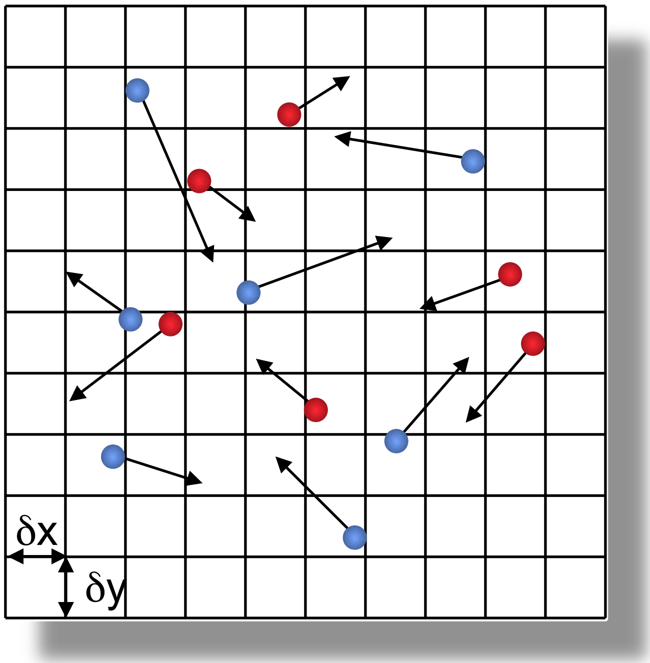
=> Need self-consistent multiphysics computing.

Examples of beams in plasmas simulations in HIFS

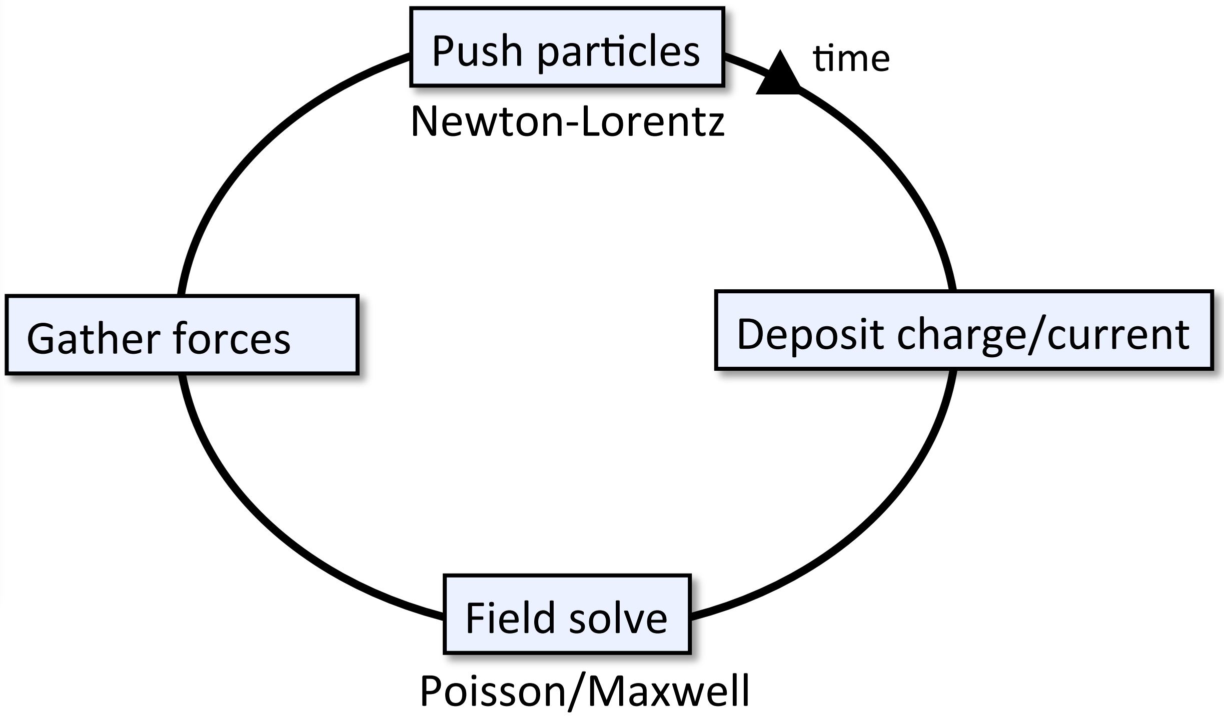
- Beam transport in HIF chamber
- Physics of beams in plasmas
- Neutralized Drift Compression (NTX, NDCX, NDCX-II)
- Electron cloud effects (HCX)
- Formation of high charge states HIF beams (Future HIF driver design)

Codes: BIC (Langdon et al), BPIC (Vay), BTRAC (Barboza), LSP (Voss S.), Warp (Grote et al) are based on the Particle-In-Cell (PIC) method.

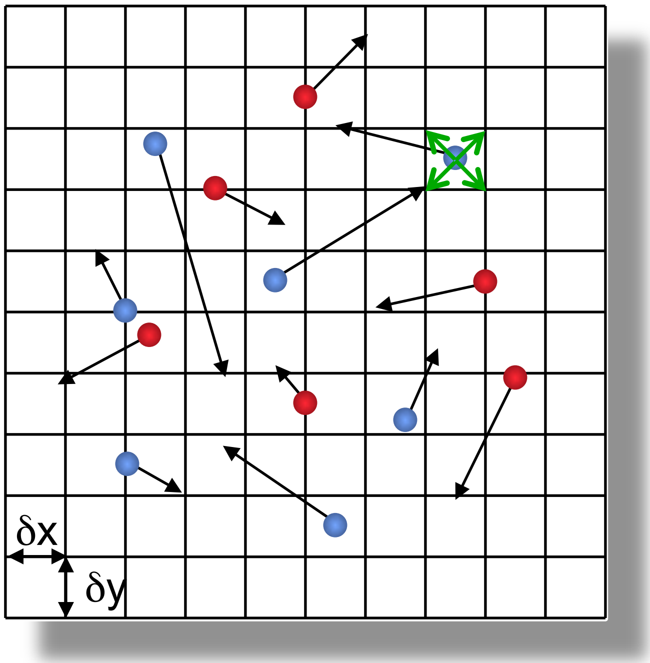
Particle-In-Cell workflow



Plasma=collection of interacting charged particles



Particle-In-Cell workflow



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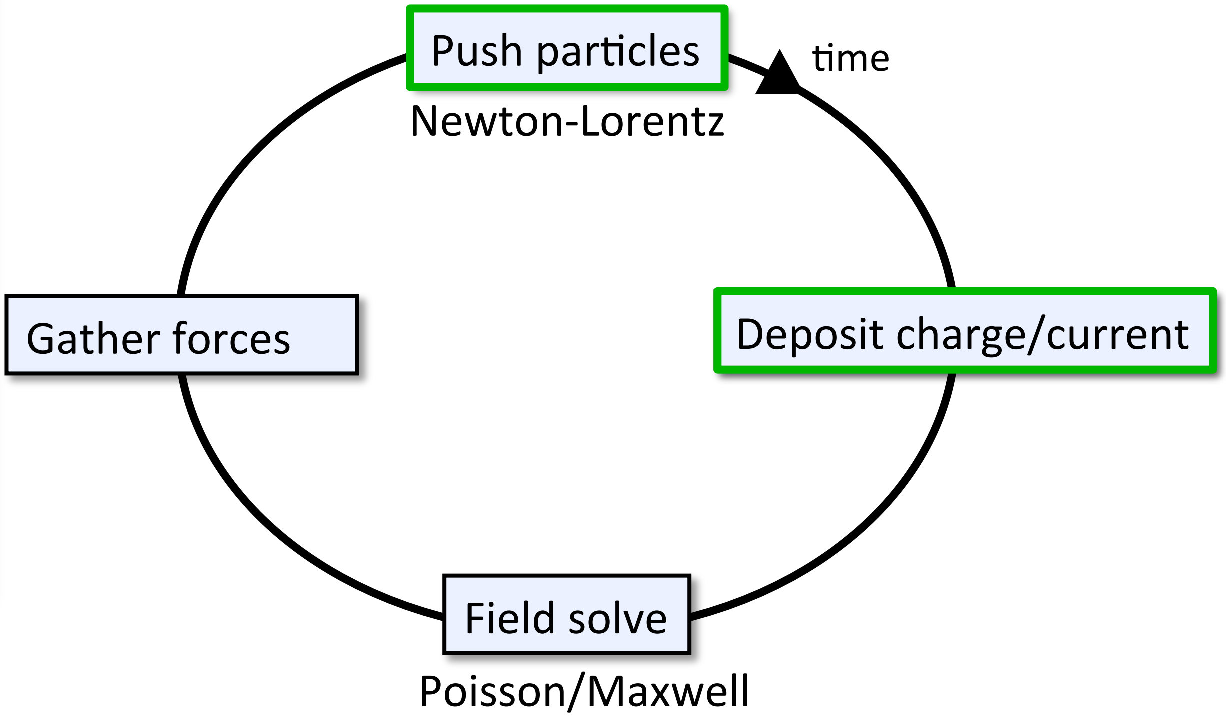
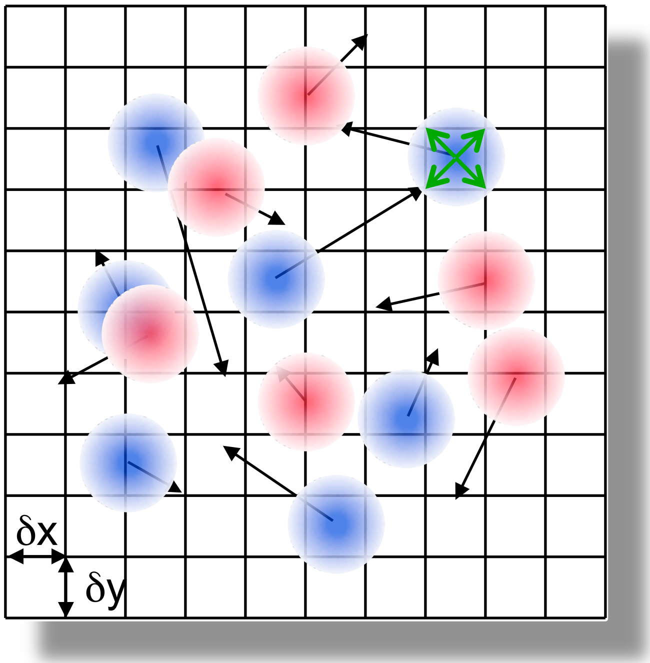


Particle-In-Cell workflow



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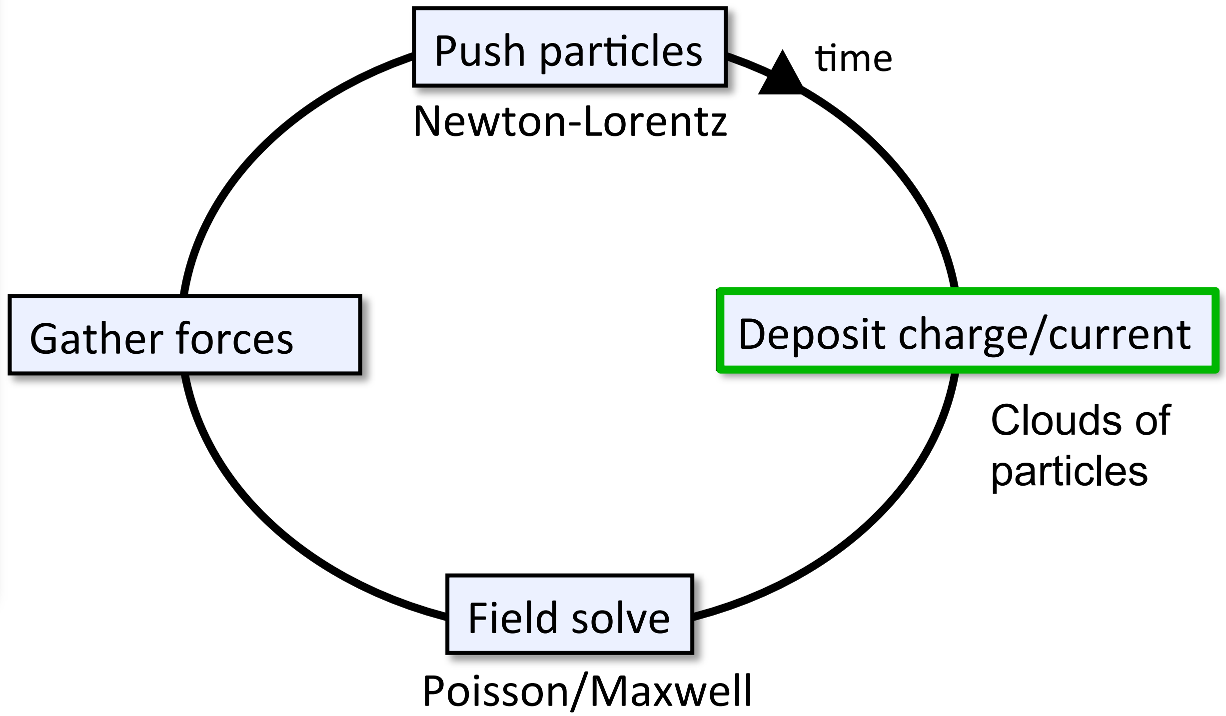
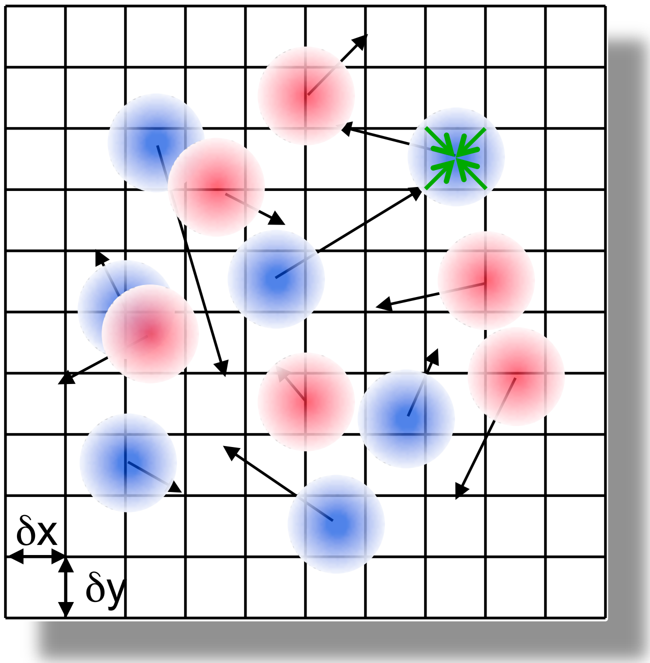


Particle-In-Cell workflow



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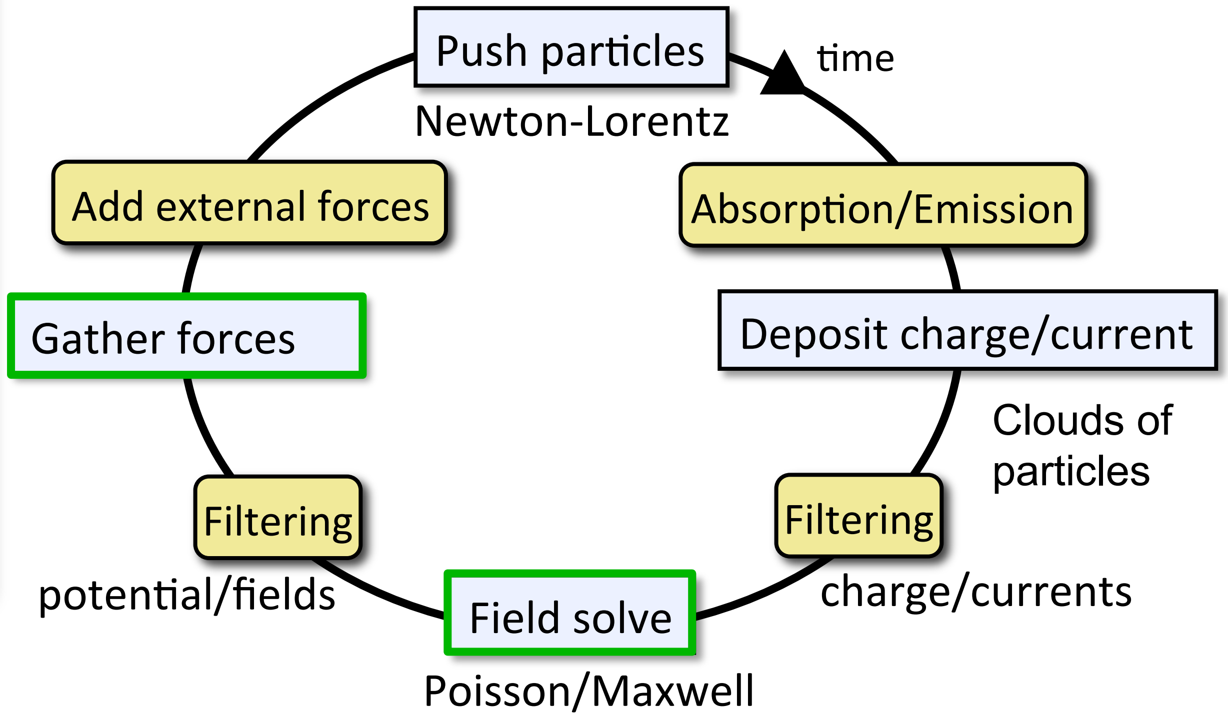

+ filtering (charge,currents and/or potential,fields).

+ absorption/emission (injection, loss at walls, secondary emission, ionization, etc),

+ external forces (accelerator lattice elements),

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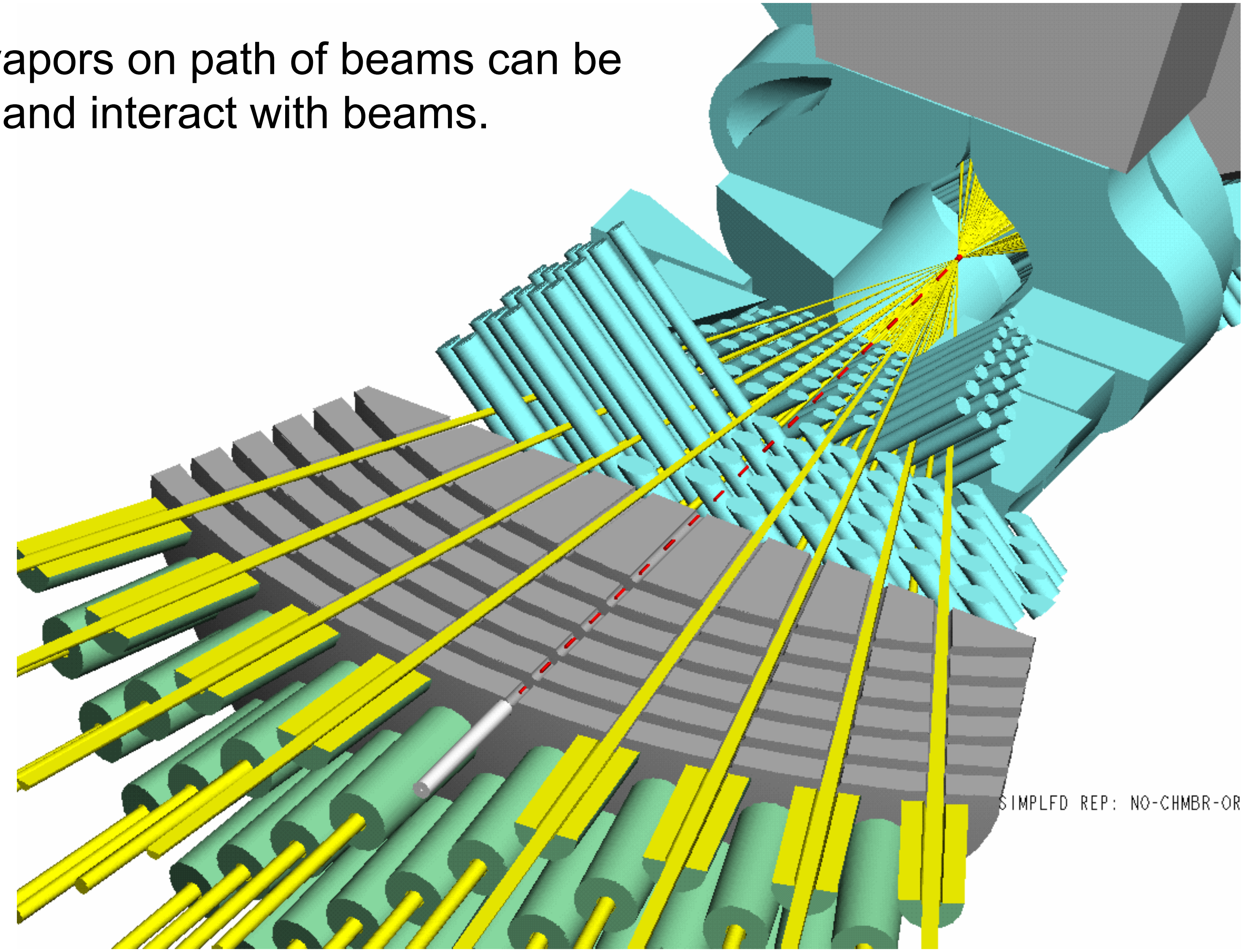
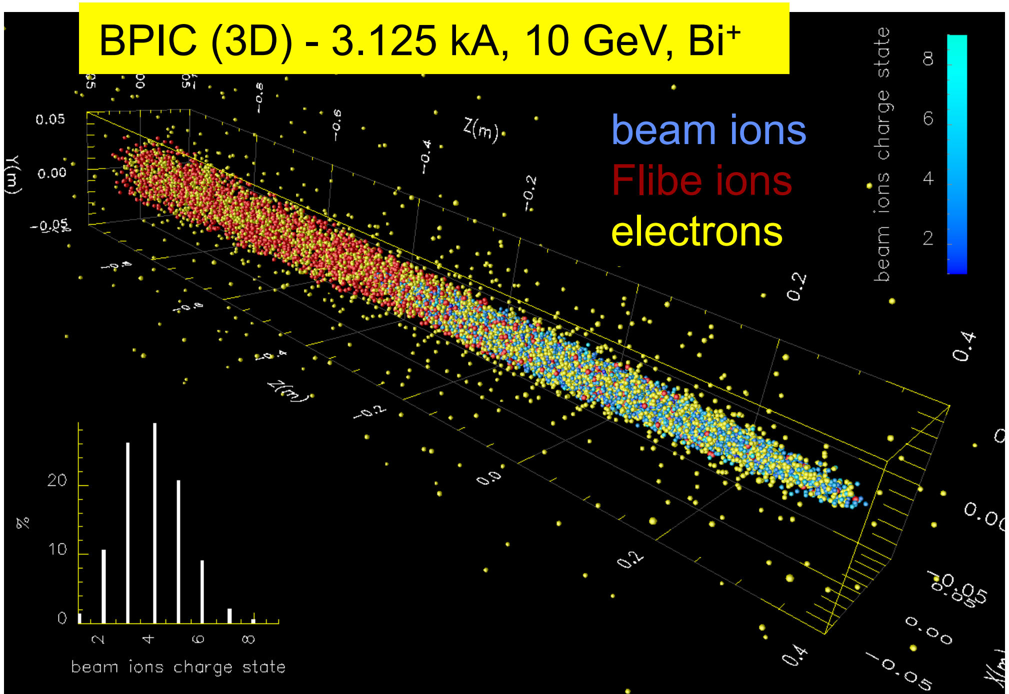
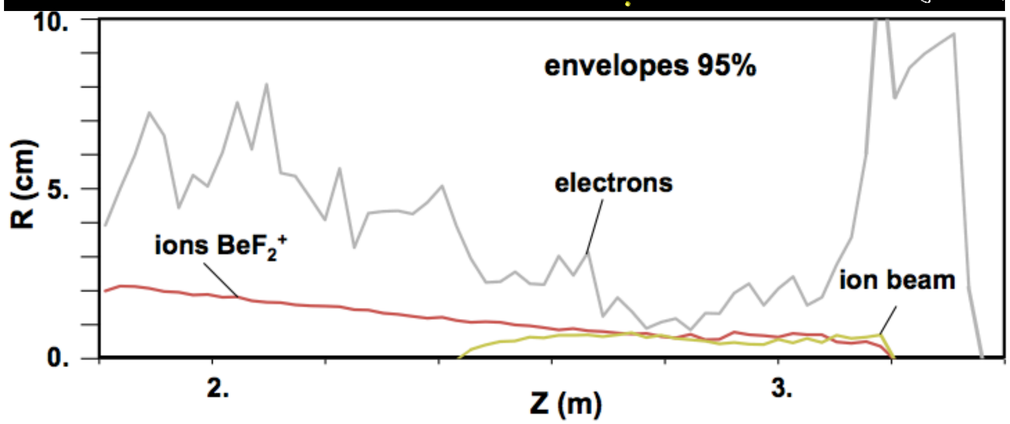
Cut-away view shows beam and target injection paths for an example thick-liquid chamber (Hylife II design)

Liquid vapors on path of beams can be ionized and interact with beams.

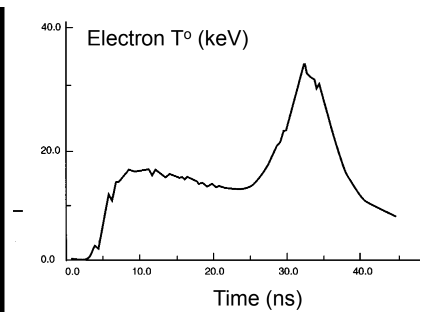


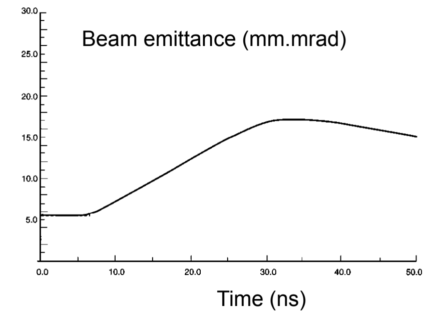
Simulation of ballistic transport through FLIBE





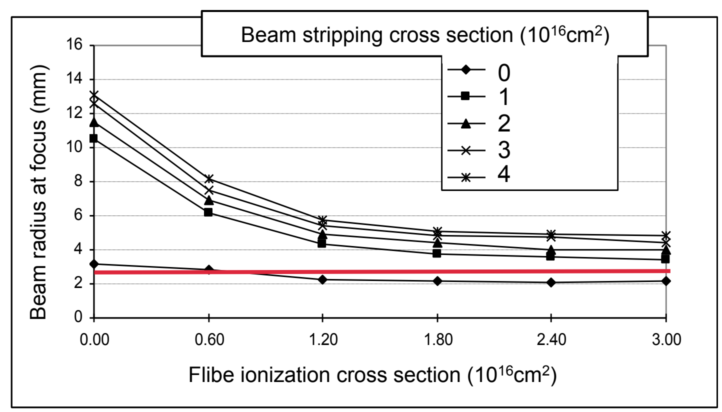
Vay et al, Phys. Plasmas 5 (1998)





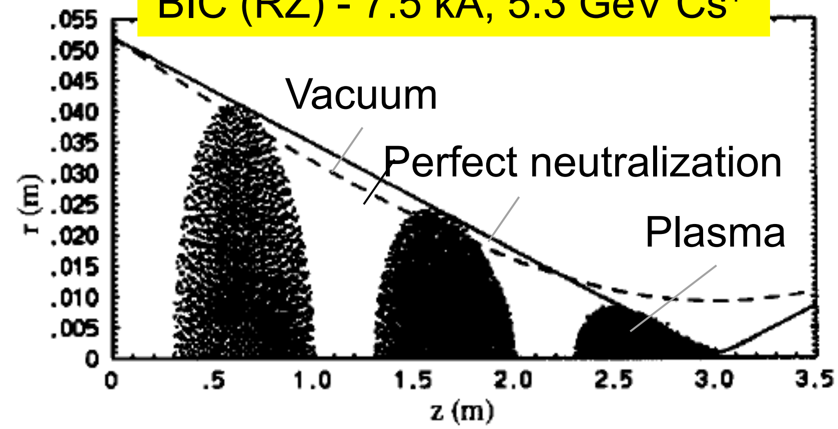
Transverse compression leads to raising electron temperature, imperfect neutralization and emittance growth.

Uncertainties on gas ionization & beam stripping cross sections constrain the background Flibe to low densities.



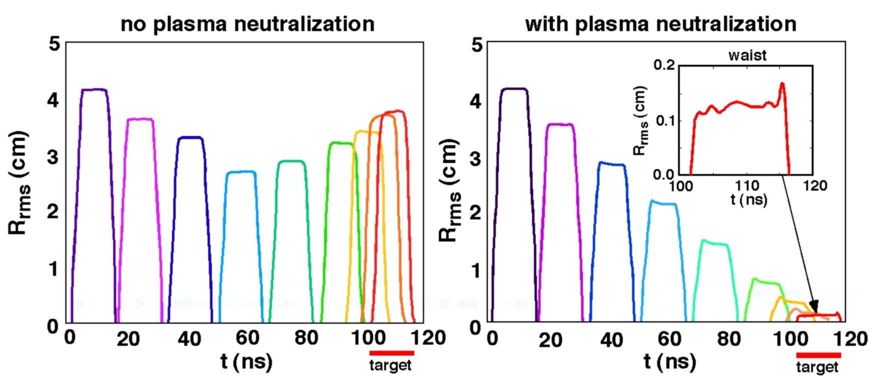
A preformed plasma channel provides better neutralization

BIC (RZ) - 7.5 kA, 5.3 GeV Cs^+



Callahan et al, Fus. Eng. Des. 32 (1996)

LSP (3D) – 2 kA, 4 GeV, Bi^+



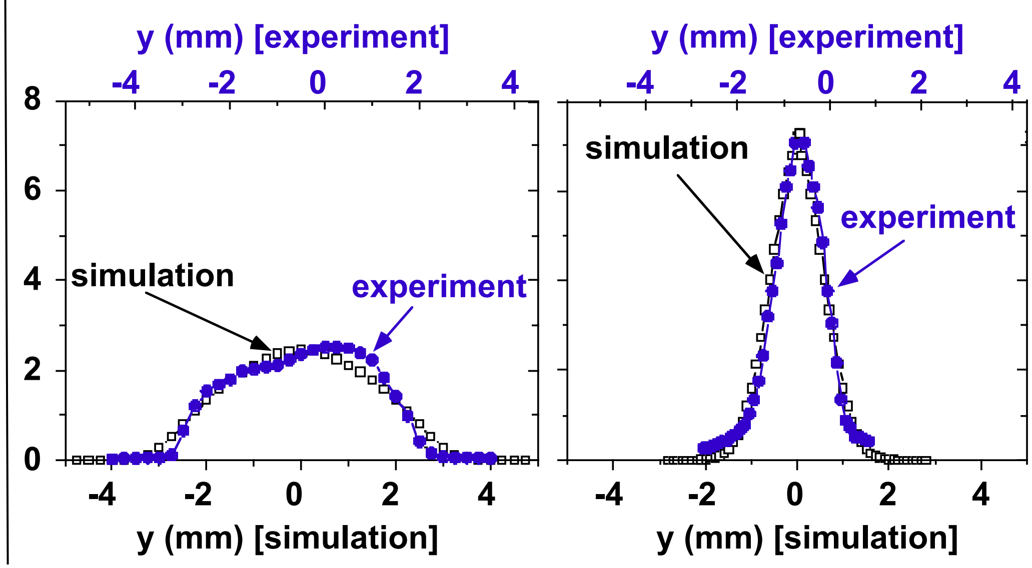
Sharp et al, Nucl. Fusion 44 (2004)

Benchmarking performed against Final-Focus Scaled Experiment, studying effect of neutralizing electrons (from a hot filament) on focal spot size.

400μA, 160 keV, Cs^+

Unneutralized beam

Partially neutralized beam



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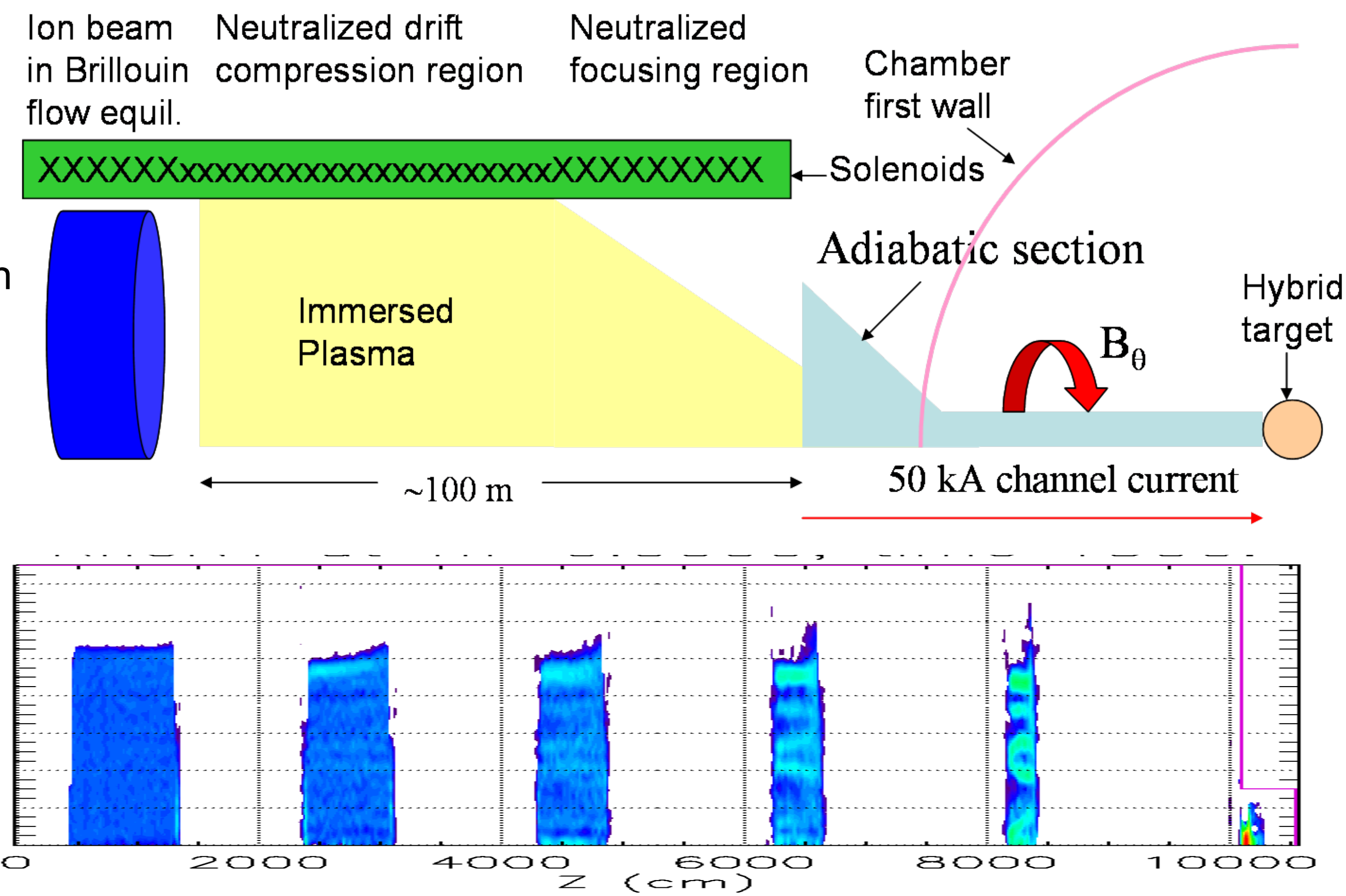
Integrated simulation of final focus design for NDC with discharge transport for HIF driver

Plasma response (yellow and blue regions) modeled with a scalar conductivity in LSP



Welch et al, HIF 2004

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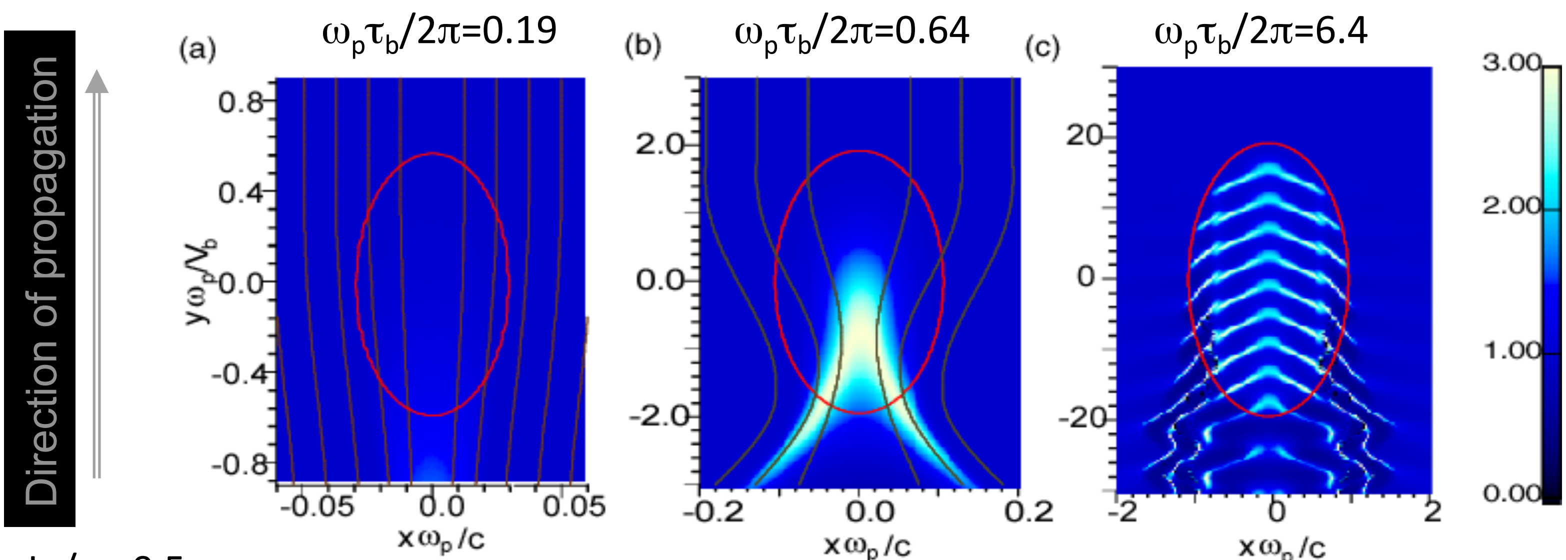
Simulations also help us understand beam flows in plasmas

Charge neutralization depends on pulse duration and plasma frequency.



$V_b=L_b/\tau_b=0.5c$
$n_b=0.5n_p$

LSP simulations

Criterion for near complete neutralization: $\omega_p\,\tau_b/2\pi>>1$.

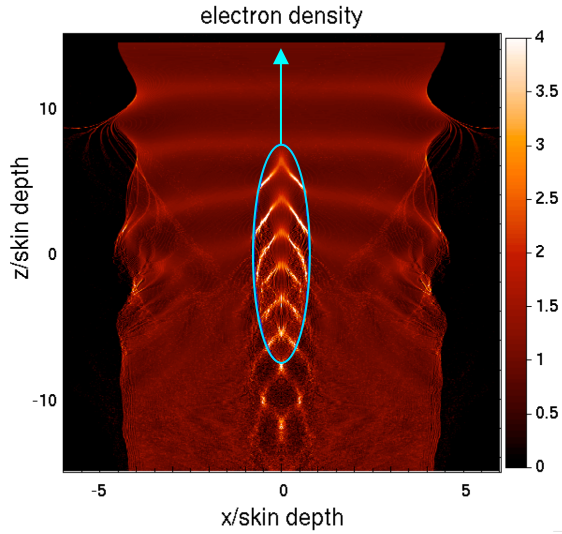
Kaganovich et al, Phys. Plasmas 11 (2004)

Reproduced with Warp in 2D and extended to 3D

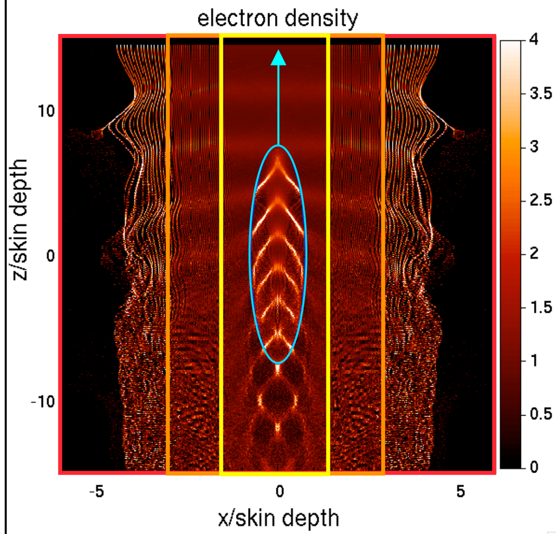
no refinement

2 levels of mesh refinement (MR)

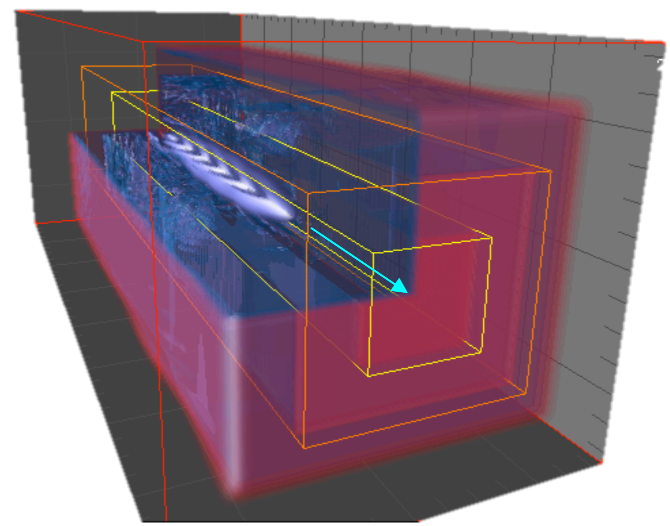
2-D high resolution



2-D low resolution + MR



3-D



Warp's mesh refinement enabled 3D simulations (speedup x10 in 3D).

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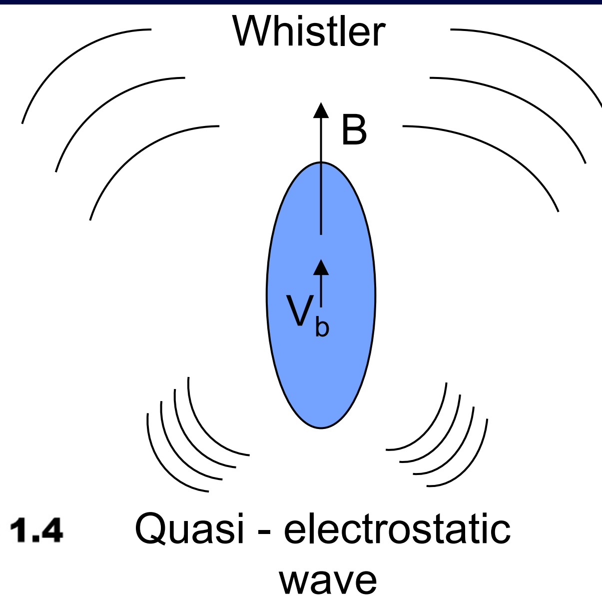
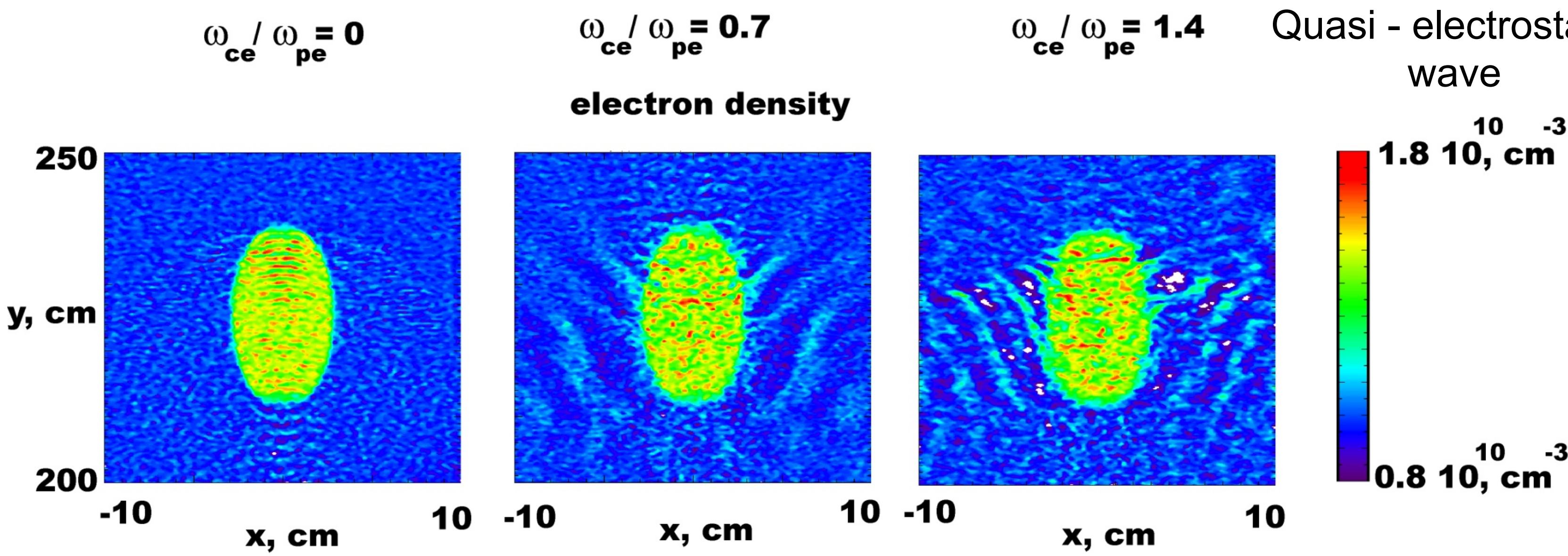
Solenoidal magnetic field influences the waves in plasma

Plots of electron charge density contours in (x,y) space, calculated in 2D slab geometry using the LSP code with parameters:

Plasma: $n_p=10^{11}cm^{-3}$; Beam: $V_b=0.2c$, 48.0A, $r_b=2.85cm$ and pulse duration $\tau_b=4.75$ ns.

A solenoidal field of 1014 G corresponds to $\omega_{ce}=\omega_{pe}$.





Kaganovich et al, Phys. Plasmas 17 (2010) and this symposium.

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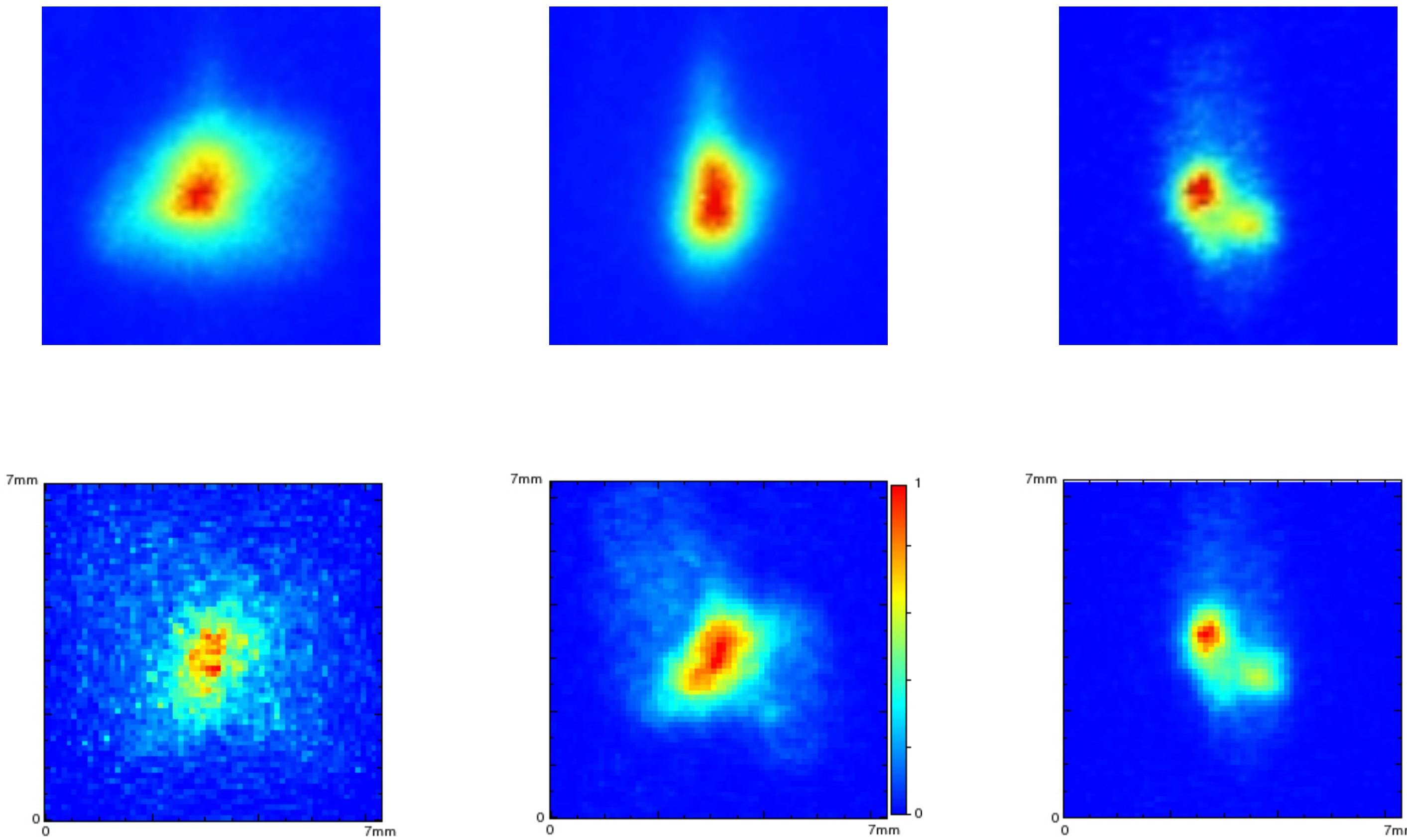
LSP was also benchmarked against plasma neutralization experiments on NTX

	With plasma plug	With plasma plug and RF Plasma	100% neutralization

NTX[1] MEASUREMENT

6-mA, 254-keV, 2-cm K^+ beam, with L = 1m

LSP[2] SIMULATIONS



[1]Roy et al, HIF 2004; [2]Welch et al, HIF 2004

Integrated source-to-target simulation of NDCX with Warp

Simulation carried out in two stages

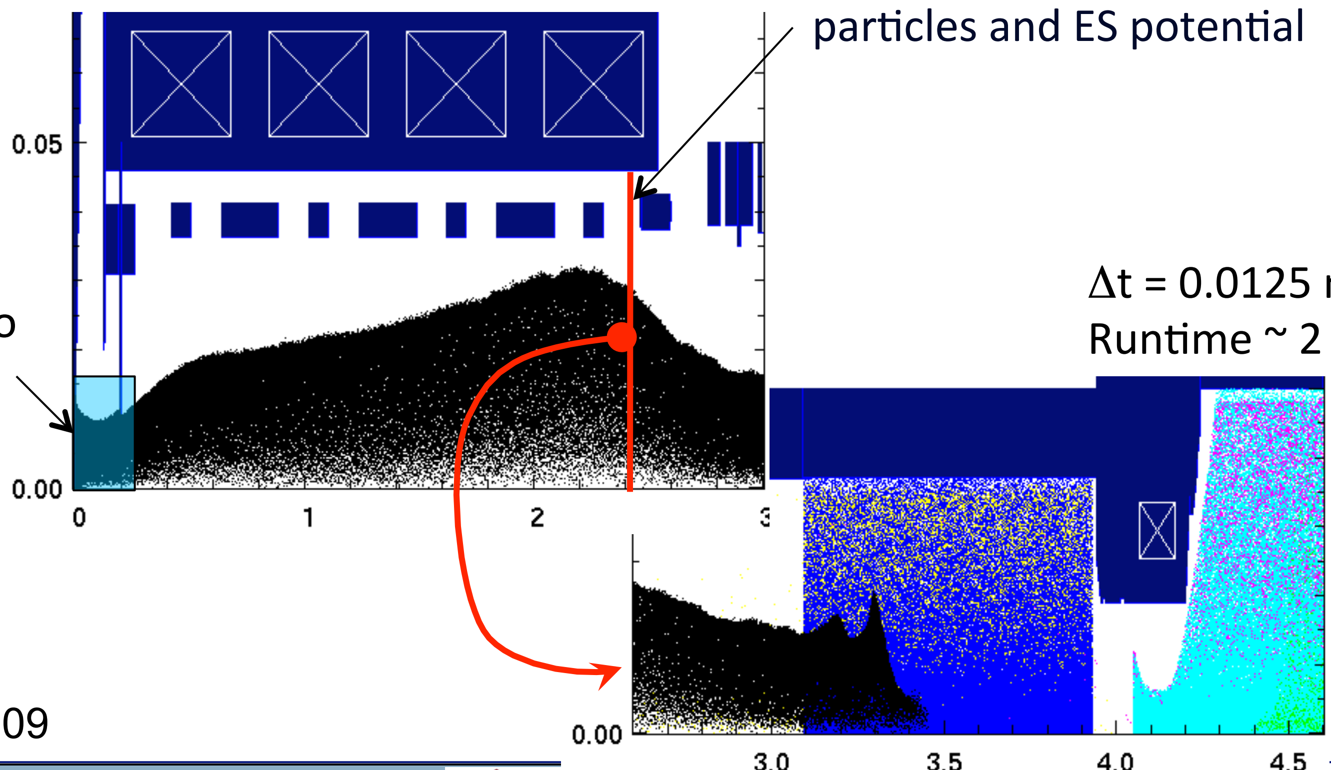
- From source to IBM – beam only so use large Δt
- From IBM to target – with plasma, so constrained by $\omega_{pe}\Delta t < 1$

Δt = 1.25 ns
Runtime ~ 1 hour

Mesh refinement to capture details of the source

Transition at a plane, saving particles and ES potential

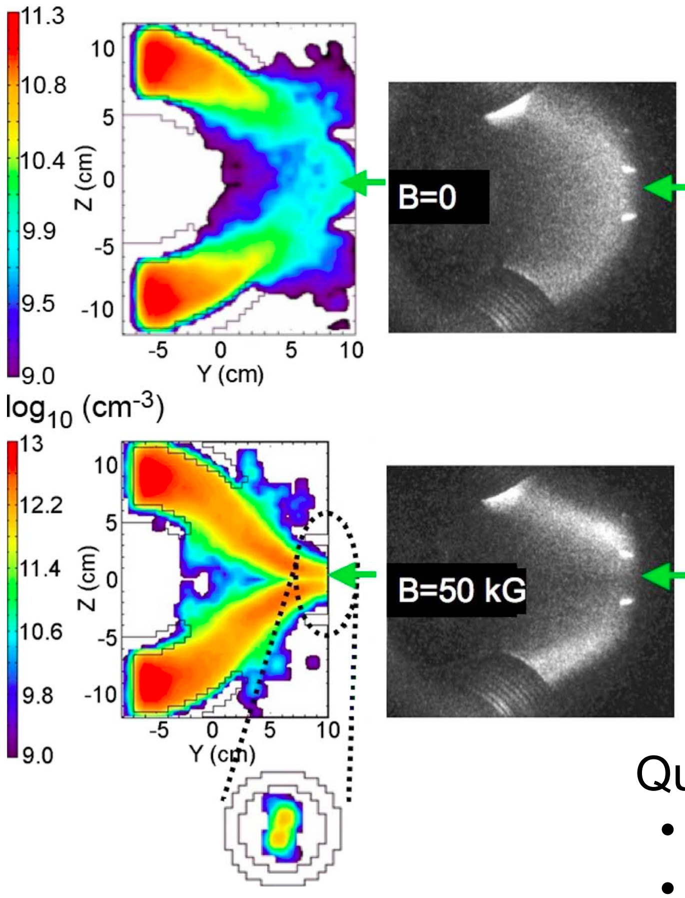
Δt = 0.0125 ns
Runtime ~ 2 days



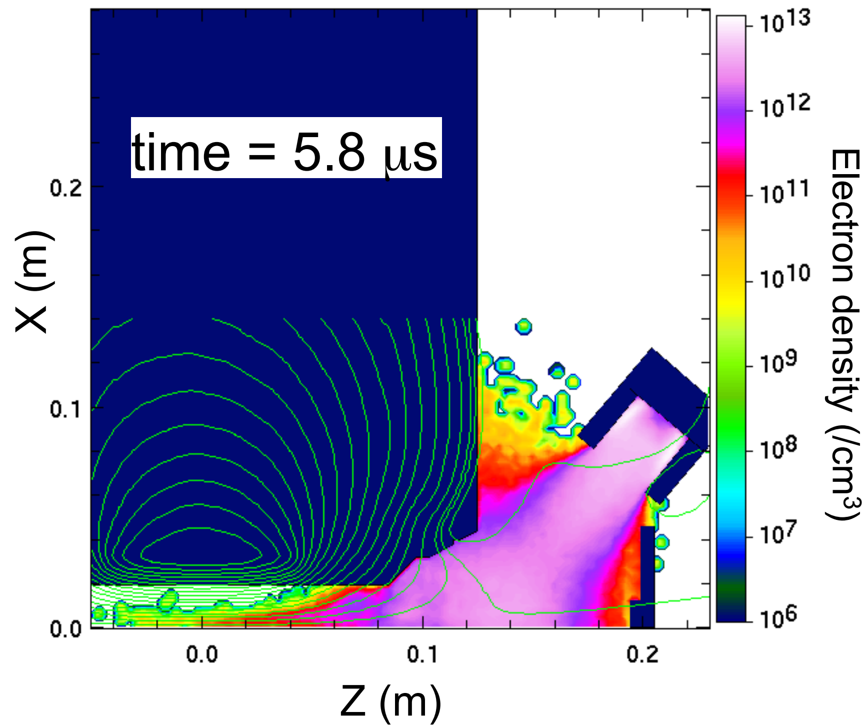
Grote et al, ICAP 2009

PIC simulations of the injection of the neutralizing plasma

LSP NDCX



Warp



Qualitative agreement found with experiment:

- Similar density profile on axis
- Rapid radial falloff in density at round 4-5 mm radius

Sefkow et al, Phys. Plasmas 16 (2009)

Grote et al, ICAP (2009)

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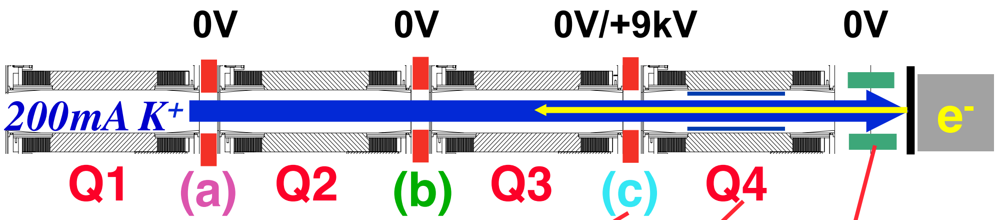
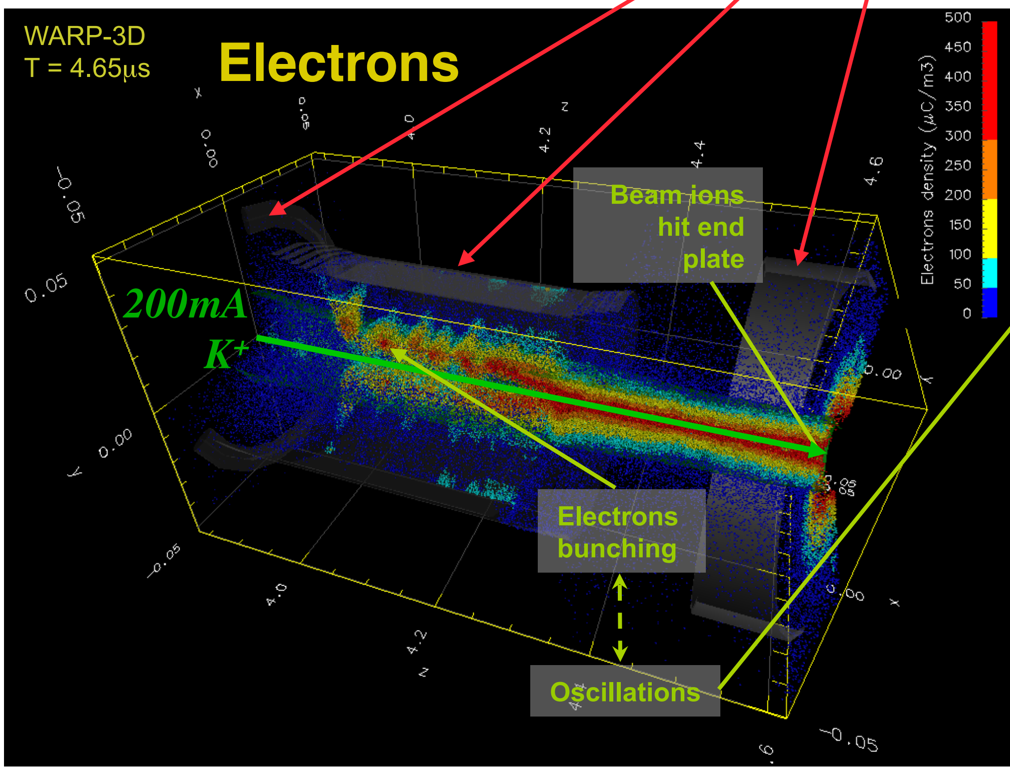
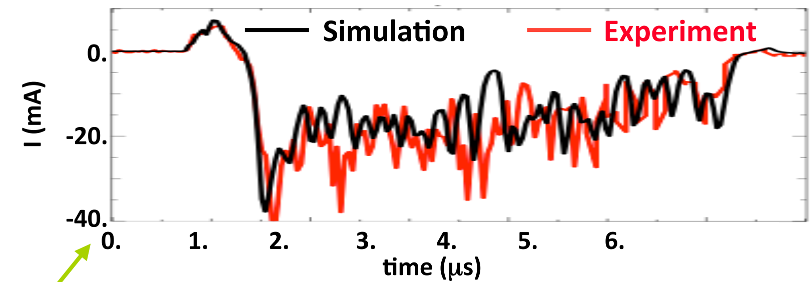
Modeling of the interaction of beam with electrons in a quadrupole

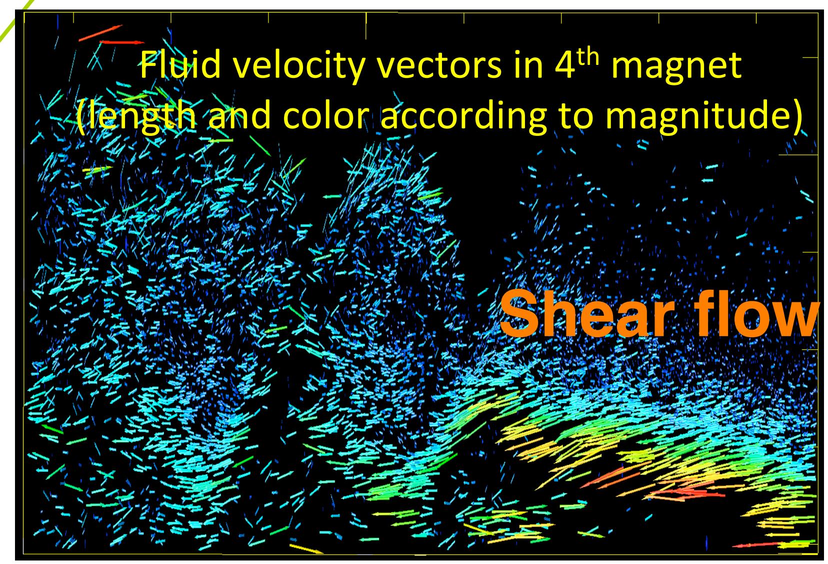
High Current Experiment (HCX)





~6 MHz signal in (C) in simulation AND experiment

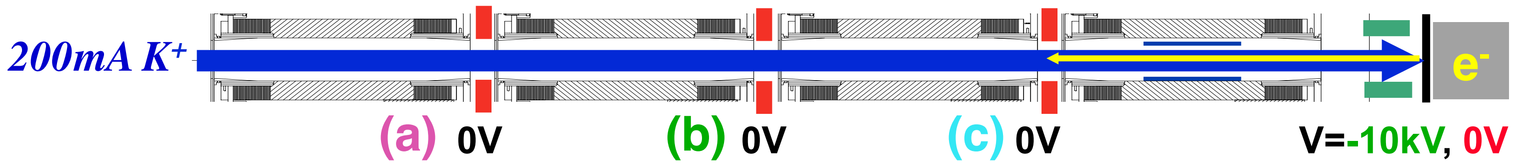




Vay et al, HIF 2006

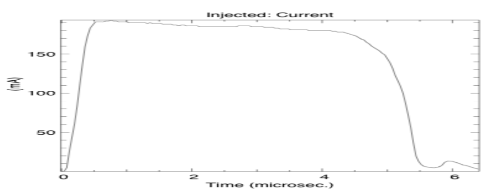
Study of oscillations pending: Kelvin-Helmholtz, two-stream, other?

Effects of electrons on beam in good qualitative agreement

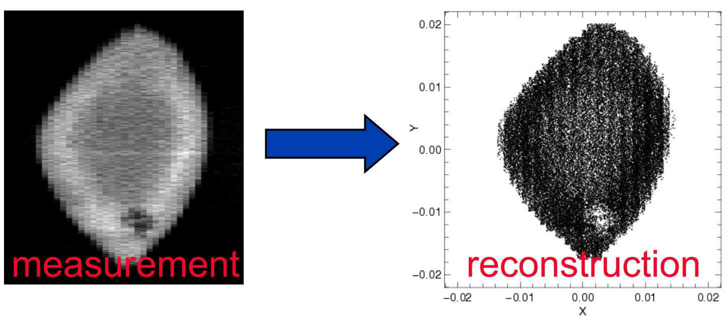


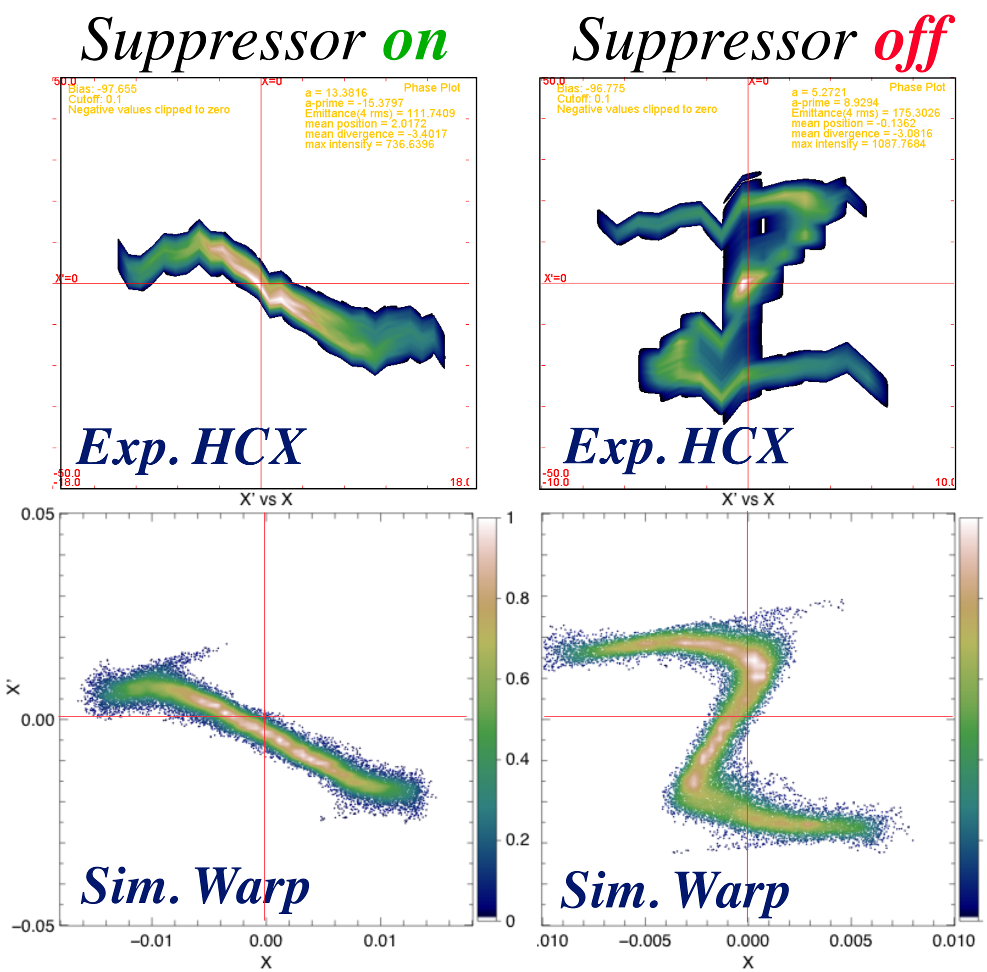
Time-dependent beam loading in Warp from moments history from HCX data:

- current



- energy
- **reconstructed** distribution from XY, XX', YY', XY', YX' slit-plate measurements





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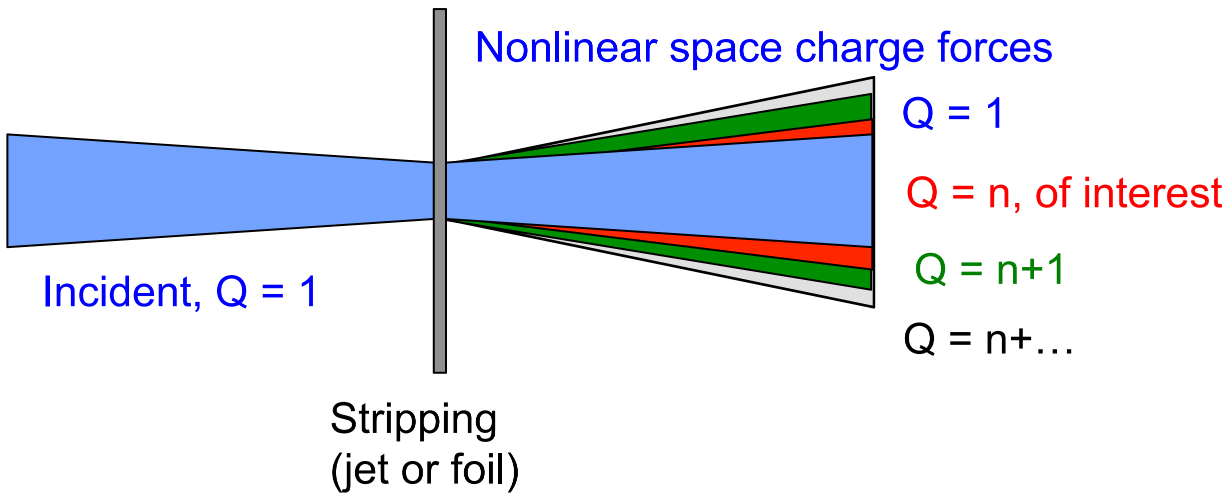
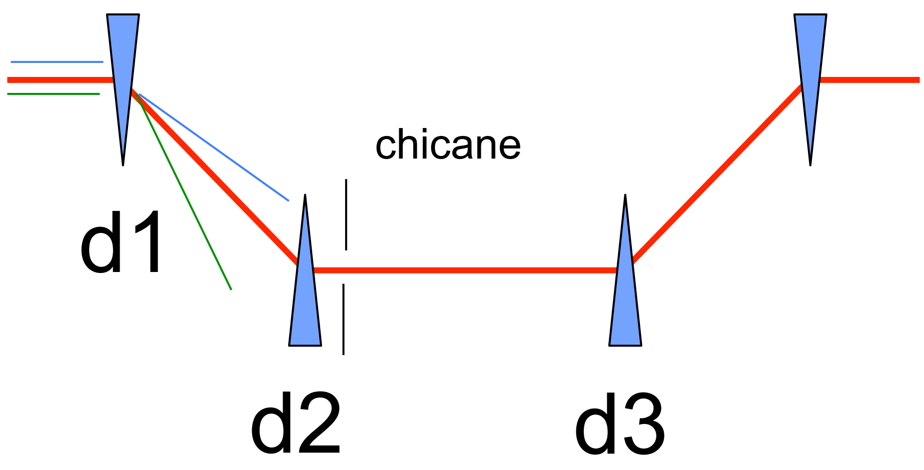
Formation of high charge states HIF beams : challenges

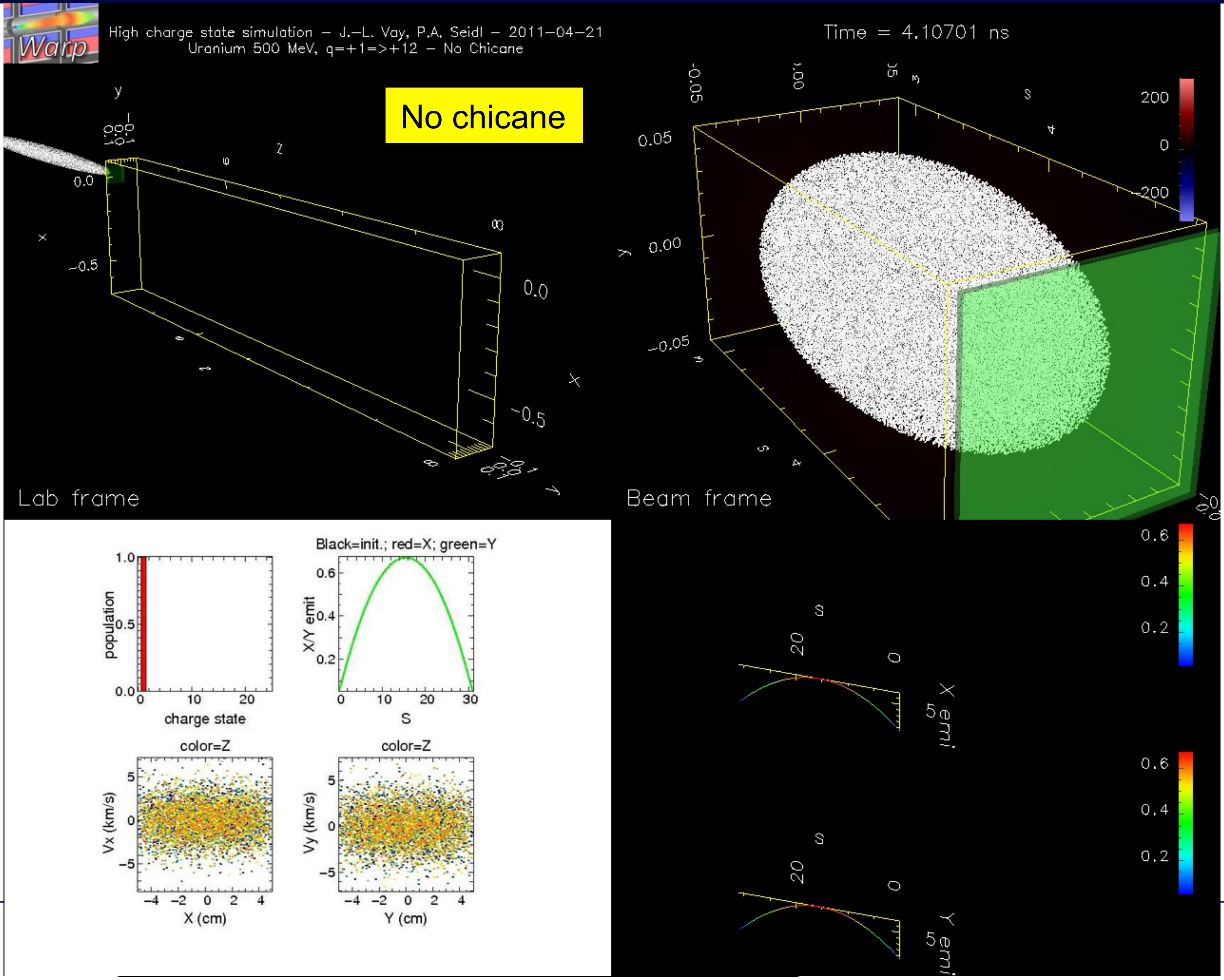


- emittance growth due to space charge
- separation of charge states
- particle loss to walls or in dumps
- gas load, heat load on stripping target
- effect of secondary e⁻ on the ion beam
- longitudinal energy spread (straggling)
- Implementation in a multiple beam linac



Seidl et al, PAC 2011

Example: 500 MeV, $U^+ \rightarrow U^{12+}$ (2.1 MeV/amu), $\beta = 6.7 \times 10^{-2}$, I_o = 11 A, ε_{un} = 10 mm•mrad, $\varepsilon_{norm} \approx \varepsilon_{un} \bullet \beta$ = 0.67 mm•mrad.



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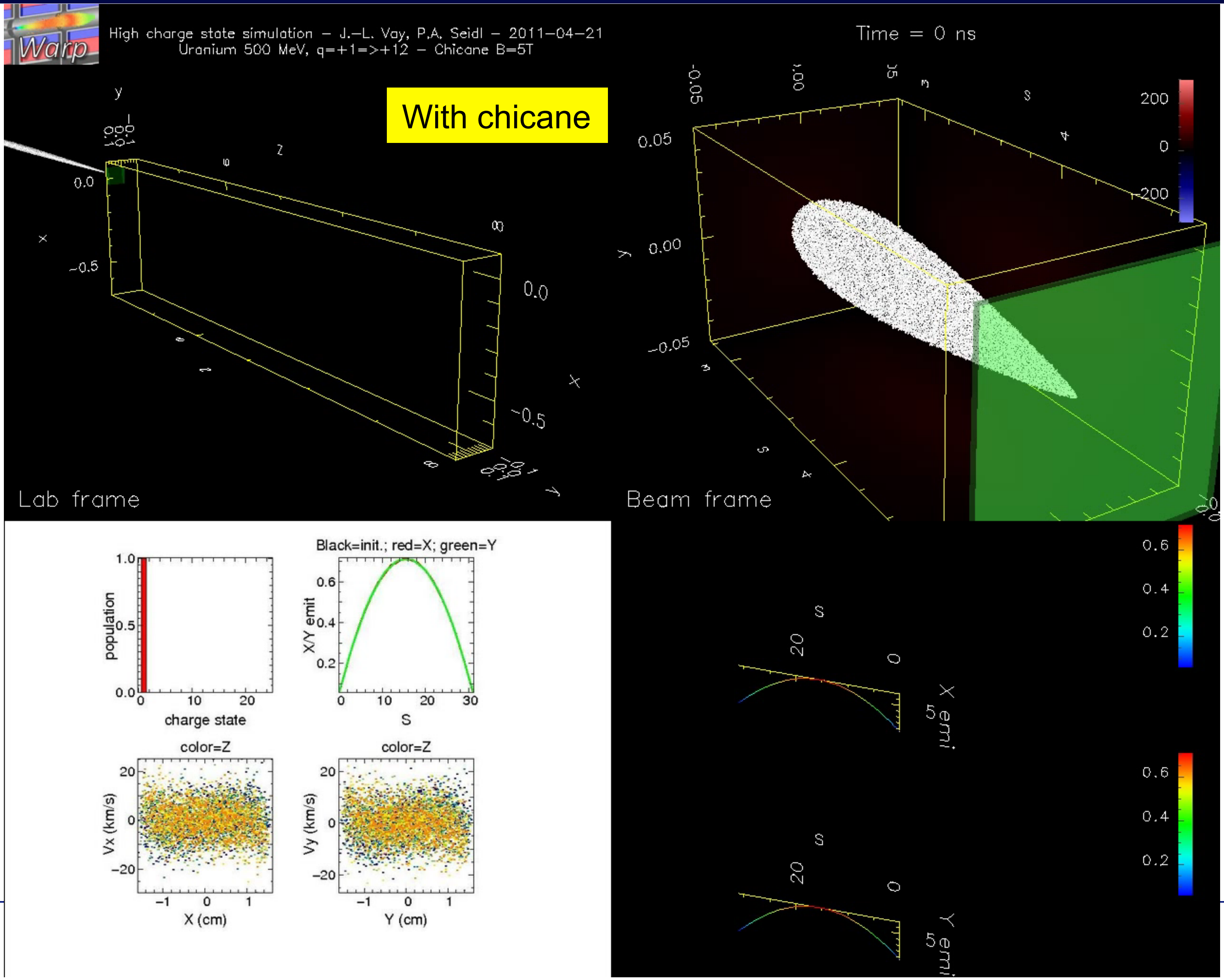

Summary

- The study of the propagation of beam(s) in plasma (neutral and non-neutral) is an important component of the HIFS portfolio:
    - front end: high-charge state beams
    - accelerator: electron cloud effects
    - final focus and chamber propagation: neutralized drift compression, discharge transport, etc

- Several codes and methods have been used and developed by the HIFS program